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Abstract: Prestressed concrete sleepers are essential structural components of railway track structures, with the purpose of redistributing wheel loads from the rails to the ground. To facilitate cables and signalling equipment, holes are often generated in these prestressed concrete sleepers. However, the performance of these sleepers under impact loading may be a concern with the addition of these holes. Numerical modelling using finite element analysis (FEA) is an ideal tool that enables static and dynamic simulation and can perform analyses of basic/advanced linear and nonlinear problems, without incurring a huge cost in resources like standard experimental test methods would. This paper will utilize the three-dimensional FE modelling software ABAQUS to investigate the behaviour of the prestressed concrete sleepers with holes of varying sizes upon impact loading. To obtain the results that resemble real-life behaviour of the sleepers under impact loading, the material properties, element types, mesh sizes, contact and interactions and boundary conditions will be defined as accurately as possible. Both Concrete Damaged Plasticity (CDP) and Brittle Cracking models will be used in this study. With a better understanding of how the introduction of holes will influence the performance of prestressed sleepers under impact loading, track and railway engineers will be able to generate them in prestressed concrete sleepers without compromising the sleepers' performance during operation.

1. Introduction

Railway sleepers are a primary component in the railway track system, playing a significant role of transferring vehicle loads to the track structure below it. Other functions of the sleeper include maintaining the track gauge and providing insulation for the rails against electricity. While they may be constructed of materials such as steel, plastic composites, and timber, concrete sleepers are generally preferred for their better performance, flexibility for specific service requirements, and longer life-span.

Although concrete enjoys the listed merits, a main concern is that it is susceptible to deterioration issues. Cracks may occur in a sleeper which may expand and cause the latter to fail over time, and this could incur extra costs to replace them as they cannot be repaired after sustaining considerable damage.

A possible source of damage that may induce cracking in sleepers is the impact loads on track systems. It is discovered that impact loads may be resulted from the interaction between the vehicle and the track, and the resonance produced among track components [1]. Despite the low cycle of impact loads, they may however cause severe damage to sleepers due to their high magnitude.

Given that holes are often drilled into sleepers for signalling equipment, this raises a concern that they may increase the risk of sleepers cracking and failing under impact loading. To make matters worse, there are limited studies pertaining to this concern. Hence, a better understanding of their behaviour under impact loading may be required to ensure that they have a life span which could in turn mean better returns on investment on the sleepers.

2. Finite element modelling

The commercial FE analysis software ABAQUS has been utilised for this study [2], where two methods are used for the FE sleeper models used in this research: The Concrete Damaged Plasticity models and the brittle cracking models.

The CDP models allow the resemblance of the behaviour of concrete by enabling strain hardening during compression and stiffness recovery, and the sensitivity to the straining rate can be adjusted accordingly. Heavy distortion may be avoided through the frequent re-meshing nature of the impacted zone during analysis, if adaptive meshing is adopted with CDP models. The CDP model is suitable for analysing models under cyclic loading conditions.

The brittle concrete models meanwhile, contain a failure criterion and the removal of elements during the analyses. This means that the crack propagation of the sleeper under impact loading can then be thoroughly examined, which is unachievable by using CDP models.

2.1 Elements and Mesh Sizes

There are four primary segments used for the model, which are the concrete sleeper, the prestressed tendons, the wheel, and the rail. The element sizes are 15, 35, 12 and 10 respectively. All components except the prestressed tendons are of C3D8R element type, while the prestressed tendons are of the C3D6 element type [3]. The element types and sizes were chosen to ensure accurate results while reducing the time for calculation and computational accuracy for contact analysis. Figure 1 shows the constructed mesh of the model setup.

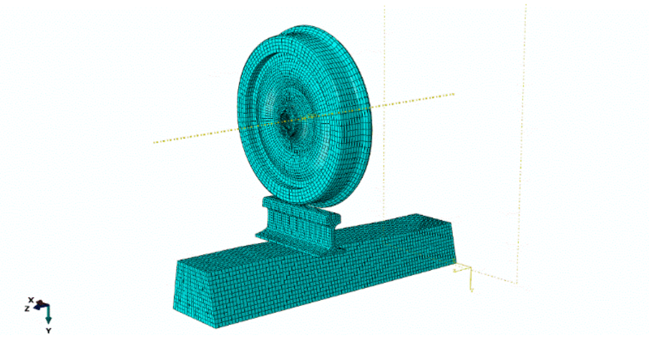

Figure 1 - Constructed mesh of sleeper model

2.2 Contact definition

General contact has been defined for the entire model and a friction coefficient of 0.3 was applied for the interaction between the structural components.

2.3 Boundary Conditions

There are 3 main boundary conditions applied to the models, to replicate a real-life sleeper under impact loading. A vertical velocity of 1.94 m/s was applied at the center of the wheel and its DOF is constrained except the U2 direction [1,4,5] as shown in Figure 2, allowing it to resemble the motion of an impact loading. Roller boundary conditions are applied on the bottom of the sleeper as shown in Figure 3, acting as the supports of the sleeper.

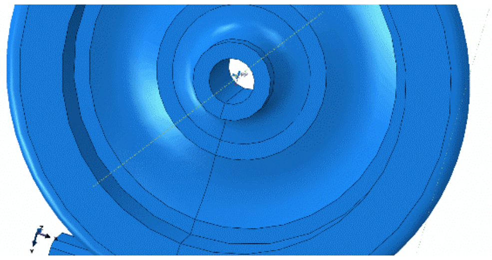

Figure 2. Boundary Condition at Wheel

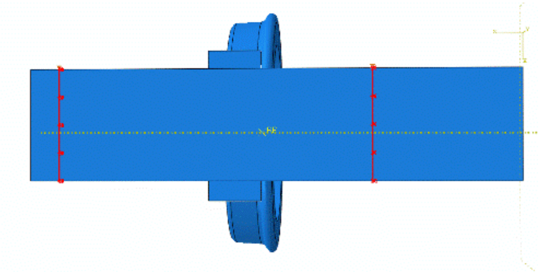

Figure 3. Boundary Condition under sleeper

2.4 Constraint definition

The following constraints have been defined in the models as shown in Table 1.

Table 1. Constraints definition

Component	Constraint
Wheel	Rigid
Surface between rail bottom and sleeper top	Tie
Prestressed tendons and concrete sleeper	Embedded Region

2.5 Material Properties

2.5.1 Concrete

The sleeper component is made of concrete and the typical properties of normal concrete that have been registered for the models, are listed in Table 2. The plasticity, tensile, and compressive properties used for the CDP models are listed in Tables 3, 4 and 5 respectively. Meanwhile the brittle behaviour and the brittle failure criteria are listed in Tables 6 and 7.

Table 2. Typical properties of normal concrete

Density ρ_c	Young's Modulus E_c	Poisson's Ratio v_c	Compressive Strength σ_{cc}	Tensile Strength σ_{ct}	Fracture Energy *GF*
2400 kg/m^3	36406 MPa	0.2	60 MPa	2.85 MPa	154 N/m

2.4.1.1 Concrete Damaged Plasticity (CDP)

Table 3. Plasticity input for CDP model

Dilation Angle	Eccentricity	Fb_0/fc_0	K	Viscosity Parameter
45	0.1	1.16	0.0067	0

Table 4. Tensile behaviour for CDP model

Yield Stress (MPa)	Fracture Energy
2.56	0.15

Table 5. Compressive behaviour for CDP model

Yield Stress (MPa)	Inelastic Strain
27.78650201	0
36.27619362	0.001
43.73984458	0.00125
49.88530231	0.0015
54.54914425	0.00175
57.70881121	0.002
59.46422457	0.00225
60	0.0025
59.54281442	0.00275
58.32516972	0.003
56.56074572	0.00325
54.43140618	0.0035
52.08318636	0.00375
49.62794701	0.004
32.10818842	0.006
21.33143134	0.008
15	0.01
11.07686332	0.012

2.5.1.2 Brittle Cracking Model [6]

Table 6. Brittle behaviour for brittle cracking model

Direct stress after cracking	Direct cracking strain	Field 1
3.17	0	0.5
0	0.0008	0.5
4.5	0	1.5
0	0.0008	1.5

Table 7. Brittle failure input for Brittle Cracking model

Failure Criteria	Direct cracking failure strain or displacement
Unidirectional	0.045

2.5.2 Steel and Prestressed steel tendon

The general properties of the steel used for the wheel, rail and tendons are assumed in Table 8 below.

Table 8. General properties of steel

Density ρ_s	Young's Modulus E_s	Poisson's Ratio v_s
7.8 g/cm^3	200 GPa	0.3

Table 9 summarises the plastic stress-strain relationship for the prestressed tendons.

Table 9. Plastic stress-strain property for prestressed steel tendon

Yield Stress (MPa)	Plastic Strain
1000	0
1703	0.0085
1750	0.0097
1797	0.01
1860	0.064

3. Validation

It is imperative to validate the FE models to ensure legitimate results. The developed models were calibrated to static loading conditions, for the validation against the results obtained in Erosha Gamage's research [7,8]. The ultimate bending moment at failure for the developed models was compared to the experimental and numerical results obtained in his research. The validation results can be seen in Tables 10, 11, 12 and 13, where positive correlations can be observed between the results for the models and the results from Erosha's research.

Table 10. CDP model validation against experimental results

Sleeper Case		Max Bending Moment at Rail Seat (kNm)		Difference (%)
		Experimental	FEA (CDP)	
No hole/web opening		67	66.3	1.04
Longitudinal hole	32mm	65	64	1.54
	42mm	61	59	3.28
Transverse Hole	32mm	57	59	3.51
	42mm	56	56	0
Vertical hole	32mm	65	65	0
	42mm	61	63	3.28

Table 11. CDP model validation against Erosha's FEA

Sleeper Case		Max Bending Moment at Rail Seat (kNm)		Difference (%)
		Erosha's FEA	FEA (CDP)	
No hole/web opening		65.7	66.3	0.91
Longitudinal hole	32mm	62.2	64	2.89
	42mm	59.4	59	0.67
Transverse Hole	32mm	55.5	59	6.31
	42mm	55	56	1.82
Vertical hole	32mm	63	65	3.17

	42mm	59	63	6.78

Table 12. Brittle Cracking model validation against experimental results

Sleeper Case		Max Bending Moment at Rail Seat (kNm)		Difference (%)
		Experimental	FEA (Brittle Cracking)	
No hole/web opening		67.0	66.3	1.82
Longitudinal hole	32mm	65.0	64.0	4.84
	42mm	61.0	59.0.	0.16
Transverse Hole	32mm	57.0	59.0	0.18
	42mm	56.0	56.0	1.41
Vertical hole	32mm	65.0	65.0	1.25
	42mm	61.0	63.0	2.71

Table 13. Brittle Cracking model validation against Erosha's FEA

Sleeper Case		Max Bending Moment at Rail Seat (kNm)		Difference (%)
		Erosha's FEA	FEA (Brittle Cracking)	
No hole/web opening		65.7	65.8	0.15
Longitudinal hole	32mm	62.2	62.0	0.32
	42mm	59.4	61.1	2.78
Transverse Hole	32mm	55.5	57.1	2.80
	42mm	55.0	56.8	3.17
Vertical hole	32mm	63.0	64.2	1.87
	42mm	59.0	62.7	5.90

4. Conclusion

This paper has examined the structural behaviour of railway sleepers with holes under impact loading by using finite element modelling. This includes the study of the load-deflection relationship, Von Mises Stress distribution and crack propagation of every case listed in the paper. It was then determined in both the CDP and Brittle Crack models that the sleeper with a 42mm transverse hole has the worst performance of all the cases under impact loading. This insight will probably help railway and track engineers to make critical decisions on the type of holes to generate in sleepers for signalling equipment without compromising the structural integrity of the sleeper.

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